

**IMPACTS ASSESSMENT OF PLUG-IN HYBRID VEHICLES ON ELECTRIC UTILITIES
AND REGIONAL U.S. POWER GRIDS
PART 1: TECHNICAL ANALYSIS**

Michael Kintner-Meyer
Kevin Schneider
Robert Pratt
Pacific Northwest National Laboratory^(a)

ABSTRACT

The U.S. electric power infrastructure is a strategic national asset that is underutilized most of the time. With the proper changes in the operational paradigm, it could generate and deliver the necessary energy to fuel the majority of the U.S. light duty vehicle fleet. In doing so, it would reduce greenhouse gas emissions, improve the economics of the electricity industry, and reduce the U.S. dependency on foreign oil. Two companion papers investigate the technical potential and economic impacts of using the existing idle capacity of the electric infrastructure in conjunction with the emerging plug-in hybrid electric vehicle (PHEV) technology to meet the majority of the daily energy needs of the U.S. LDV fleet.

This initial paper estimates the regional percentages of the energy requirements for the U.S. LDV stock that could be supported by the existing infrastructure, based on the 12 modified North American Electric Reliability Council (NERC) regions, as of 2002, and taking into account congestion in regional transmission and distribution systems. For the United States as a whole, 84% of U.S. cars, pickup trucks and sport utility vehicles (SUVs) could be supported by the existing infrastructure, although the local percentages vary by region. Using the light duty vehicle fleet (LDV) classification, that includes cars, pickup trucks, SUVs, and vans, the technical potential is 73%. This has a gasoline displacement potential of 6.5 million barrels of oil equivalent per day, or 52% of the nation's oil imports. The paper also discusses the impact on overall emissions of criteria gases and greenhouse gases as a result of shifting emissions from millions of individual vehicles to a relatively few number of power plants. Overall, PHEVs reduce greenhouse gas emissions with regional variations dependent on the local generation mix. Total NO_x emissions may or may not increase, dependent on the utilization of coal generation in the region. Total SO_x emissions increase in all but 3 regions. Particulate emissions increase in 8 of the 12 regions. The emissions in urban areas are found to improve across all pollutants and regions as the emission sources shift from million of tailpipes to a small number of large power plants in less-populated areas. This paper concludes with a discussion about grid impacts as a result of the PHEV load as well as the likely impacts on the plant and technology mix of future generation capacity expansions.

The second paper (Part II: Economic Assessment) discusses the economics of the new PHEV load from the perspective of a load-serving entity. It discusses the potential downward pressure on rates as revenues increase in the absence of new investments for generation, transmission, and distribution.

^(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC05-76RL01830

INTRODUCTION

The U.S. electric infrastructure is designed to meet the highest expected demand for power and, as a result, is underutilized the majority of the time. The system operates at its full capacity only a few hundred hours a year, at most (about 5% of the time). For the remainder of the time, the power system could generate and deliver a substantial amount of energy needed to fuel the nation's light duty vehicle fleet (LDV): cars, pickup trucks, sport utility vehicles (SUVs), and vans. This paper estimates the percentage of the U.S. LDV fleet that could be supplied with energy from the existing U.S. power system without additional investments in generation, transmission, and distribution (T&D) capacities. This paper postulates an electric-vehicle scenario that is based on the concept of plug-in a hybrid electric vehicle (PHEV). A PHEV is a hybrid electric vehicle with additional battery-storage capacity sized to satisfy the daily average driving requirements (33 miles per day), solely on electricity. The battery is charged with electricity from the electric grid during off-peak hours, most of which occur during the night. Driving beyond the daily driving range (i.e., long distances) requires that the PHEV's gasoline engine be used. The analysis of this paper determines the upper limit of the PHEV penetration without requiring new investment in generation and T&D capacity expansions. The fundamental approach used is equally valid for a pure electric vehicle with similar electric performances of a PHEV.

In this paper, we frame the discussion by first describing the methodological approach for estimating the existing idle generation capacity to be used for PHEV charging and then comparing the resulting generation figure (in MWh) to the energy requirements of the U.S. LDV fleet for daily driving. The resulting percentage of the LDV fleet constitutes the upper limit of the electrification potential for the LDV fleet, displacing gasoline fuel with electricity. We presume that the transmission and distribution system would be capable of delivering the electricity to the new PHEV load and present the rationale for this assumption. Assuming that the upper limit of the technical-fuel-displacement potential would occur, we discuss the question of what are the net impacts to the overall emissions as the emission source shifts from millions of vehicle tailpipes to a smaller number of large power plants. There are favorable economic impacts associated with a high fuel-displacement scenario. PHEVs provide power sales revenues without requiring additional new infrastructure. This translates into additional profits and, from a regulated electricity industry point of view, downward pressure on rates. The economics from both the electricity providers' and the customers' point of view are presented in the companion paper (Part II: Economic Assessment).

BACKGROUND

In his 2006 State of the Union address,¹ President George W. Bush identified the U.S. dependency on foreign oil as a major national security issue. In the United States, transportation is the largest consumer of petroleum products of any economic sector. As a consequence, cars, vans, and light duty trucks are a logical target for alternative fuel supplies. High oil prices during 2005, exacerbated by the supply disruption in gasoline products in the aftermath of hurricanes Katrina and Rita, brought concerns about the supply of petroleum to the attention of the public.

¹ State of the Union Address available at <http://www.whitehouse.gov/>.

These events have increased efforts to identify options to petroleum, including biofuels and hydrogen. For the reasons noted by the President and national security experts, the faster the United States can reduce reliance on petroleum, the better. Rapid transition to new alternative fuels will require significant investment in new fuel production and distribution infrastructure. This is not the case for PHEVs, as the necessary charging infrastructure is already in place. As new alternative fuels enter the market, they can be used in PHEVs to further reduce the need for imported petroleum products.

METHODOLOGICAL APPROACH

The study is divided into two analytical components. The first is an analysis of the upper limit of PHEV penetration using off-peak power for charging the battery. The second is an analysis that assesses the impacts on the overall emissions as electricity displaces gasoline in the LDV fleet.

We used a conservative approach to identify the maximum utilization of PHEVs by restricting our analysis on the existing electric infrastructure. In other words, this is a worst-case scenario that does not include expansion of generation and T&D capacity as PHEVs make inroads into the market place, increase the electric load, and alter the load shape. Because we do not know when and at what rate PHEVs may penetrate the market, nor do utility planners, constraining our analysis to the current power system infrastructure appears to be a defensible and plausible approach.

Estimating existing idle electric generation capacity in a region is based on a “valley-filling” methodology in which the margin between the installed system capacity and the system load is determined. The system load is based on the North American Electric Reliability Council (NERC) data for 2002. Because of the large regional differences in the load profiles and the generation mix, the analysis is performed for 9 eastern NERC regions as well as the 3 sub-regions of the Western Electricity Coordinating Council (WECC). The results from these 12 areas are aggregated to discuss the results from a national perspective. The Energy Policy Act of 2005 resulted in significant changes in the structure of the NERC regions. Because the data used for analysis pre-date the Energy Policy Act of 2005, this analysis is based on the regional structure as it existed in 2002.

Particular attention was given to the issue of power transfers that occur between regions. In some cases, a region’s native generation will be supplemented by inter-region power transfers, while in others, the native generation will supply a load that exists outside the region. When determining the generation that is available to recharge PHEV batteries within a region, power transfers into and out of the region are taken into account.

The second component of the analysis assesses the impacts on the overall emissions as electricity displaces gasoline in the LDV fleet. We distinguish between total emissions and emissions release in urban areas with high human-health implications. The emissions analysis employs a well-to-wheel analysis of the entire energy conversion path from extracting the primary energy out of the ground to delivering useful energy in the form of miles traveled. The Argonne National Laboratory’s Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is used for this analysis [GREET, 2001]. The emission analysis is performed for the 12 modified NERC regions to reflect the varying electric generation mix for charging the PHEV batteries. The analysis includes a discussion of

the shift from mobile to stationary emission sources as well. Finally, this paper discusses the petroleum-displacement opportunity for the upper-limit PHEV penetration scenario.

The sections below describe the data sources and the methodological approaches in detail.

Data Sources and Level of Aggregation

Because of large variations with respect to the electric infrastructure, generation mix, and diversity in load profiles across the United States, this analysis has been performed on a regional basis, dividing the United States into 12 regions. The definition of a region is adopted from the NERC and the Energy Information Administration (EIA) regionalization.

System load profile data were obtained from NERC. The most recent and complete data set available at the time of this analysis consists of hourly load data by NERC regions and sub-regions for the year 2002.² NERC compiles load data reported from load-serving entities to perform system assessments and reliability analyses.³ Of the 10 NERC regions, 9 are represented in their entirety in this study. WECC is disaggregated into three modified sub-regions according to EIA's definition for the Annual Energy Outlook [EIA, 2006a and 2006b]. The analysis employed the following definition of regions:

1. ECAR (East Central Area Reliability Coordinating Agreement)
2. MAAC (Mid-Atlantic Area Council)
3. MAIN (Mid-America Interconnected Network)
4. MAPP (Mid-Continent Area Power Pool). Only the U.S. segment is used.
5. SPP (Southwest Power Pool)
6. ERCOT (Electric Reliability Council of Texas)
7. SERC (Southeastern Electric Reliability Council)
8. FRCC (Florida Reliability Coordinating Council)
9. NPCC (Northeast Power Coordination Council). Only the U.S. segment is used.
10. NWP (Northwest Power Pool Area), sub-region of the WECC
11. AZN&RMP, combining two sub-councils: Arizona-New Mexico-Nevada Power Area and the Rocky Mountain Power Area within the WECC.
12. CNV, (California and Southern Nevada), sub-region of the WECC.

Figure 1 shows the 12 modified NERC regions as used in the analysis. For the northern regions that include areas of Canada, NERC identified the U.S. segments so that only the U.S. load profile could be extracted. This applied to the regions of WECC, MAPP, and NPCC. The resulting 12 regional system load profiles for the year 2002 established the main data source for this analysis. Furthermore, EIA annual cumulative generation data are used as well as the installed capacity by major fuel and plant-type for the year 2002. The EIA data are provided at the same regional disaggregation level as the NERC data set [EIA, 2006b].

² Data were obtained from NERC 2/24/2006.

³ NERC compiles system load data from different sources, including NERC's regional councils and Federal Energy Regulatory Commission (FERC) Form 714—Annual Electric Control and Planning Area Report.

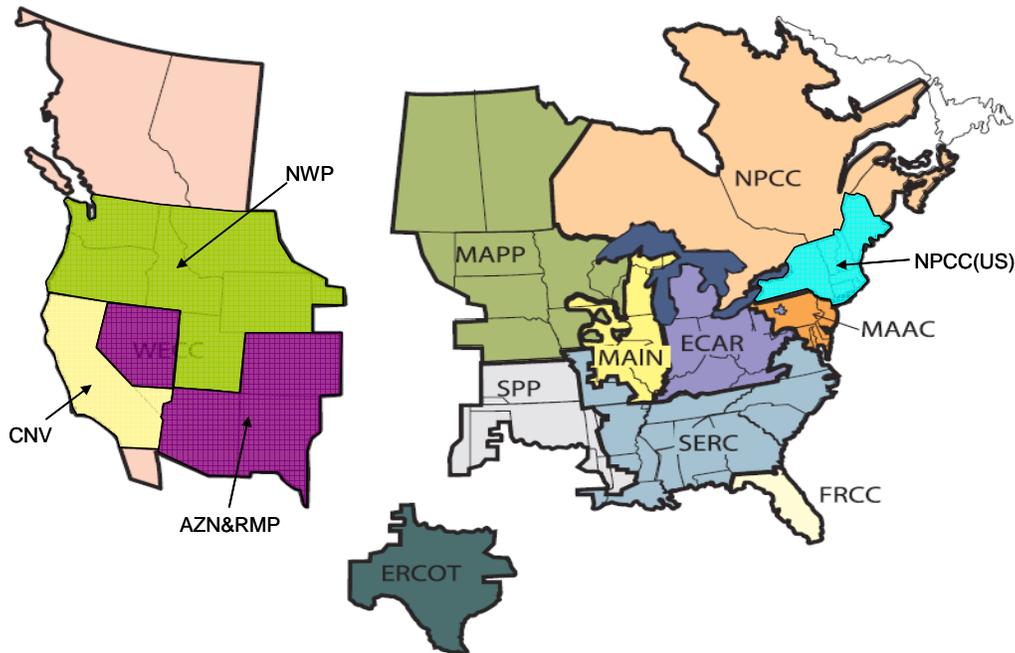


Figure 1: Definition of Regions Used in this Study—12 Modified NERC Sub-Regions Based on the Pre-1/1/2006 Regional Council Structure⁴

Vehicle Stock and Vehicle Utilization Data

The source for the U.S. vehicle stock is the 2001 motor vehicle registration, by states, as published by the U.S. Department of Transportation [DOT, 2002]. Registration figures were chosen for cars, light trucks, SUVs, and vans, generally referred to as LDVs. Motorcycles are not included. Approximately 217 million vehicles were registered in the LDV category in 2001. Registrations for cars, pickup trucks, and SUV alone amounted to 198 million. Other heavier vehicles, such as busses and trucks, are not considered in this study, although there are no technical reasons that would prevent busses and trucks from adopting plug-in hybrid electric technology. This analysis strictly focuses on light duty vehicles, excluding motorcycles.

The average daily driving per person is determined using detailed household travel survey data collected in 2001 [Davis, et al. 2006]. This survey estimated miles per year traveled in daily trips by personal vehicles to be approximately 12,000 miles per year per vehicle or about 33 miles per day per vehicle. Although this figure is strictly valid for personally-owned vehicles, we assign it to all vehicles, including commercial vehicles. This simplification may underestimate the actual daily driving of the commercial vehicles in the LDV fleet. The 33 miles per day per vehicle is then used to determine the energy requirements to be provided by electricity. It would translate to a PHEV33, which notates number of miles (33) that can be traveled in an electricity-only mode before re-charging, or the use of gasoline becomes necessary.

⁴ After 1/1/2006, the Regional Reliability Councils—ECAR and MAAC—were aggregated into Reliability First Corporation. Sections of the MAIN merged into SERC and into the Midwest Reliability Organization (MRO). More information can be found at: <http://www.nerc.com/~org/entities/>.

Other researchers in the PHEV community often cite a 1990 survey performed by U.S. Department of Transportation [Hu et al., 1994] in which the cumulative percentage of personal automobiles is plotted over the average daily travel distance per vehicle. Using data of the 1990 survey, it is frequently emphasized that 50% of personal automobiles travel 20 miles or less daily, and 70% drive 33 miles or less [Graham, 2005; Taylor, 2003]. The average daily miles traveled is about 28, slightly lower in 1990 than in the more recent survey. The cumulative percentage figures emphasize the distribution of personal driving patterns and point out that greater than 50% of personal travel will be less than 33 miles and that only a small percentage of the population drives significantly further than 33 miles per day, skewing the average upward. This means that the majority of the vehicles may not fully discharge their batteries with a 33-mile range. There will be a small population who would either drive on gasoline beyond the first 33 miles or recharge the battery sometime before they complete their daily trip, e.g., at work. Because this study assumes that each vehicle drives 33 miles per day, there is an implicit assumption that the electric energy not used to charge those that drive less is shifted to others that drive more than 33 miles per day.

Valley-Filling Approach for Estimating Available Electric Generation

The valley-filling approach requires a dispatch of the electric generators to meet the regional load demand. Once the dispatch is complete, the total installed capacity less the dispatched units sets the upper limit on the generation available for charging PHEVs. A simplified approach is chosen that reduces the complexity from an 8,760-hour dispatch (1 year), to two 24-hour dispatches, a typical summer and winter day. The simplification focuses on two limiting cases when the entire electric grid is likely to have the least reserve capacity and available generation resources for recharging the PHEV batteries. Spring and fall seasons commonly offer significantly more excess generation capacity due to reduced load demand. It is noted that reserve margins could be low during brief periods in the fall season when several power plant operators schedule planned outages for plant maintenance after high plant utilization during the summer. However, it is assumed that there is sufficient scheduling flexibility throughout the fall such that the available reserves remain always larger than during the peak summer season. This assumption will be the subject of future investigation.

The 24-hour generation dispatch is performed using a merit-order approach based on typical production costs, combined with the following rules, considering common plant operating practices. General plant type categories as defined by EIA in the Annual Energy Outlook are used [EIA, 2006a and 2006b].

- Nuclear capacity. Nuclear power plants are operated as a base-load plant at maximum generation capacity. The common capacity factor is 0.90 [EIA, 2006b].
- Coal-fueled capacity. Coal plants are operated primarily to meet base-load with capabilities to ramp up and down generation.
- Natural gas combined cycle and conventional steam plant. Plants can meet base-load and intermittent load such as load following.
- Conventional hydro capacity. Hydro systems are used to meet base-load, intermittent load, and peak load. The hydro systems in the west and the east have reached their annual generation capabilities already. Although there is significant hourly and daily generation flexibility in the installed hydro capacity, the total annual energy produced is constrained by the finite water resources and other operational requirements for wildlife preservation [BPA, 2003]

- Renewable (non-conventional hydro) energy generation. This includes wind, solar, and geothermal capacities. Renewable-energy resources are utilized to the maximum generation capability to displace conventional fossil-fuel generation.
- Peaking plants (combustion turbines). These plants are designed for a relatively short run time. Typical capacity factors for combustion turbines are in the 0.15 to 0.20 range. Although the capacity factor could be increased to some degree, the significantly higher operating costs are unlikely to make combustion turbines a viable resource for PHEVs.

The dispatch is then performed for each modified NERC region for an average summer and winter day, defined as the average hourly system load over a 3-month period. The summer period started on June 1 and ended August 31. The winter period is defined as the period from December 1 through February 28. Each average summer and winter day generation dispatch is then projected for a 6-month period, and the combined annual generation figure is compared with annual generation data. The daily profiles are adjusted to meet EIA's annual generation data as reported for 2002 in the Annual Energy Outlook 2006 (AEO2006) [EIA, 2006b]. The results of this step are two 24-hour generation dispatches representative of a typical summer and winter day.

To estimate the regional unused generation capability, we determined the difference between the total installed capacity and the hourly generation that is already committed to meeting the current load demand. This level of unused generation is further curtailed by precluding the use of peaking plants for the charging of PHEV batteries. Peaking plants are designed for relatively short run-time operations and would be uneconomical for continuous operation over long periods of time. Figure 2 illustrates the valley-filling approach.

The remaining marginal generation capacity consists of coal-fired thermal plants, natural-gas-fueled steam plants, and combined cycle plants. Not considered as marginal capacity for the valley-filling are nuclear, conventional hydro power, and renewable energy capacities because these are already fully utilized. Nuclear capacity is normally operated at its maximum capacity. Wind and solar generators are fully utilized whenever the resource is available. Conventional hydro generation is limited by finite water resources.

The installed coal and natural-gas fuel capacity is then de-rated by the capacity factor to account for planned outages. A capacity factor of 0.85 is used for both coal and natural-gas plants [EIA, 2006c]. This assumption implies that planned outages are scheduled uniformly throughout the year, which is a simplified approximation to the actual maintenance schedule. Maintenance is typically scheduled during a low-load period (commonly in the fall and spring) to make the full generation capacity available for the peak seasons. Thus, the simplified approximation for outage scheduling represents a conservative estimation of the available capacity during the summer and winter months. Petroleum-fuel steam generators, with a small contribution to the total U.S. electric generation of 3%, are grouped together with the natural-gas steam generators and are classified by EIA as "other" fossil steam generation [EIA, 2005b]. Figures A.1 through A.6 in Appendix A show the winter and summer dispatch profiles for one winter-peaking region (NWP), and two summer-peak regions (ECAR and CNV). The figures show the generation for valley-filling generation denoted as "additional" generation resources.

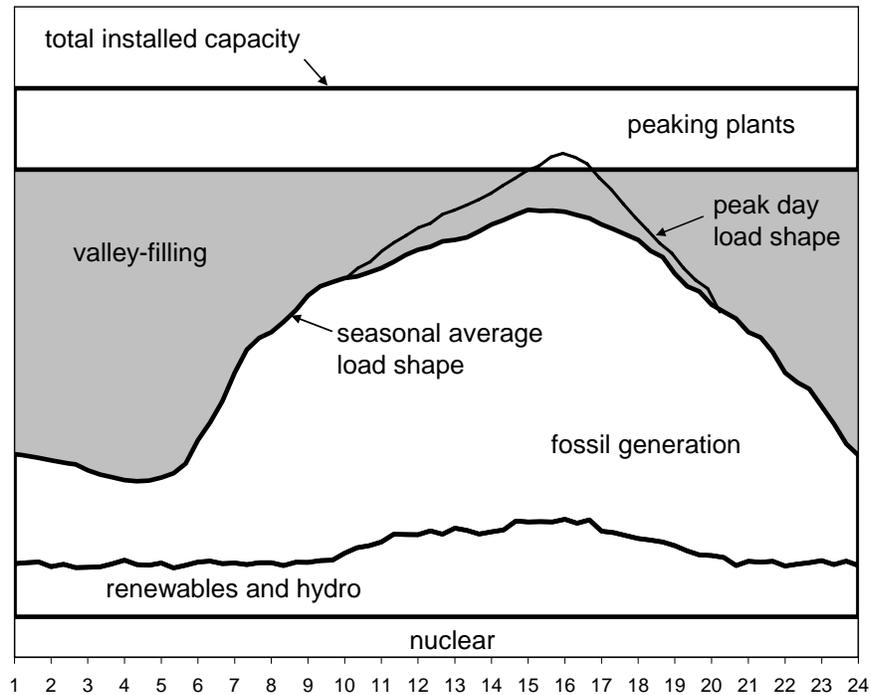


Figure 2: Stylized Load Shape for 1 Day During Peak Season, Generation Dispatch, and Installed Capacity

The margin between the system load profile and the total installed capacity after all exclusions constitutes the power available for charging PHEV batteries, in megawatts (MW). When the MWs available for charging are determined for a 24-hour period, the total energy available for charging PHEV batteries in a single day can be estimated, in megawatt-hours (MWh). This is considered the technical potential for supporting the daily recharging of the PHEVs batteries. The size of this energy block is determined for both the typical summer and typical winter day. The lower value of the two is then used as the regional representative resource estimate in MWh for PHEV battery charging.

The simplified valley-filling approach warrants the following comments:

1. Simplifying the valley-filling approach to a daily problem with a 24-hour dispatch greatly reduced the computational complexity of the resource estimation. Of interest is the limiting case or cases that impose a lower bound on the resource assessment. This particular case occurs during peak conditions when most generators are being utilized. Because the peak demand day may or may not be coincident with the day of the maximum dispatched generation, we represented the two load profiles, a summer and a winter day, to ascertain that the limited case is captured in the analysis.
2. The choice of using a seasonal average load shape rather than the load shape of the peak generation day is motivated by the dual-fuel capability of the PHEV, recognizing that there may be a few days out of the year in which the PHEV battery may not be fully recharged to its maximum storage capacity. The lack of stored electric energy will then need to be compensated for using the internal combustion engine. Restricting recharging during these periods can be accomplished through price signals or other load-control methods.

3. The available capacity for valley-filling, using coal and natural-gas plants, is de-rated by their capacity factors to represent an average availability and utilization of those plants. However, during peak seasons, most coal and natural-gas plants are typically operated to their full name-plate capacity. The 15% unavailability (capacity factor of 85%) commonly occurs during fall and spring season when the load is generally reduced, and less capacity is needed. By applying the 15% unavailability during the peak season, we underestimated the true capacity that is available.
4. By excluding peaking plants, in conjunction with de-rating the coal and natural-gas capacity by 15%, the resulting maximum demand in MW for valley-filling never exceeds the maximum system peak demand. This implies that the valley-filling method of charging PHEV batteries will never require transfers of electric power through the T&D system (at least not through the transmission system) greater than those during system peak hours (see Figure 2).

The result of the valley-filling resource estimate is a block of electric energy indicated in MWh. This energy resource then is converted into a percentage of the energy requirements for the daily driving of the regional LDV stock. The energy requirements per mile for selected light duty vehicle classes are adopted from Electric Power Research Institute’s (EPRI’s) Hybrid Electric Working Group [Duvall, 2002, 2003, and 2004] as listed in Table 1.

Table 1: Specific Energy and Energy Storage Requirements by Vehicle Classes

Vehicle Class	Specific Energy Requirements [kWh/mile]	Size of Battery for PHEV33 [kWh]
Compact sedan	0.26	8.6
Mid-size sedan	0.30	9.9
Mid-size SUV	0.38	12.5
Full-size SUV	0.46	15.2

The energy requirements of the vehicle classes above are used in the 2001 regional fleet proportions using the DOT motor vehicle registration data set. Because the DOT data set did not further specify cars into compact and mid-size, we selected an arbitrary 50/50 split. Likewise, the same split is used for the full-size and mid-size SUVs. Pickup trucks are assigned the same energy requirements as SUVs. In addition, an 8% loss in the transmission and distribution system is employed [DOE, 2003]. Efficiencies for the battery charger and the battery over a round-trip of full charge and discharge cycle are assumed to be 87% and 85%, respectively [Duvall, 2002].

Methodology for Emission Impact Analysis

The emissions impacts as a result of the additional central plant generation for charging PHEV batteries are evaluated using the GREET model. The GREET model accounts for the entire energy flow from the well of the primary energy source to the final conversion in the vehicle, propelling it 1 mile. Many assumptions are made in GREET regarding the individual efficiencies and emissions along the entire well-to-wheel energy path. This analysis adopted all of the default assumptions of the Version 1.6 model [GREET, 2001]. We used the electric vehicle definition to represent a PHEV, recognizing that we modeled a PHEV when it is operating in an electric-only mode. We excluded any mixed electric/internal combustion engine driving modes.

Key input variables to the GREET model are the composition of the existing generation mix and the additional generation dispatched for PHEVs. The GREET model uses the existing generation (in GREET parlance “average generation mix”) for all conversion processes except for electric vehicles. The electricity used to fuel electric vehicles is called “marginal generation.” The GREET model uses market shares of the generation by five fuel types (residual oil, natural gas, coal, nuclear power, and others). The average generation mix for a given region is used from the Annual Energy Outlook (AEO) 2006 regional tables for the year 2002 [EIA, 2006b]. The marginal generation is assigned using the result of the valley-filling approach, which is a combination of coal and natural-gas resources. The GREET model simulates three vehicle types (passenger cars and light duty truck, Class 1 and Class 2) for near-term and for the longer-term. We use the near-term projections, which are based on car technologies and characteristics more amenable to today’s vehicles than the longer-term projection. The vehicle types, particularly the passenger car and the light duty truck, scale relatively well such that the results expressed as a ratio of PHEV to conventional vehicle varied negligibly across the vehicle types. All results are then expressed as emission ratios.

DISCUSSION OF RESULTS

The results of the analysis indicate that significant portions of the U.S. gasoline-operated vehicle fleet could be fueled with the available electric capacity. For the nation as a whole, about 84% of the energy needed to operating cars, pickup trucks, and SUVs (or 73% of the energy of the LDV fleet) could be supported using generating, transmission, and distribution capacity currently available. This would require power providers to use the available electric generation, base-load and intermediate generation, at full capacity for most hours of the day. If charging periods are to be constrained to a 12-hour period starting at 6 pm and ending at 6 am, the technical potential would be reduced to 43% of the LDV fleet. From a regional perspective, there is some diversity in the technical potential.

The midwestern region of the United States with a significant level of coal generation could provide the necessary energy for the entire region’s LDV fleet while still exporting excess power to neighboring regions. This would require the entire 24-hour time period for recharging the PHEV batteries. The technical potential for the western regions, while still significant, is only about ½ of that of the eastern regions and about ¼ of that in the midwestern regions. A key contributing factor is the large share of hydro-electric generation, which is already at maximum sustainable generation levels. Results from ERCOT indicate it has one of the highest technical potentials because of its significant reserve capacity, some of which is taken out of service temporarily for economic reasons because of the existing excess of capacity [Potomac, 2006]. With growing electricity demand, these are expected to resume operation. Because ERCOT’s link to the eastern interconnected system has only a small transfer capability, the export capability is assumed to be negligible, requiring all of the generation to be used for intra-regional consumption. Because of the lack of export capabilities out of ERCOT, its technical potential of fueling 136% of ERCOT’s LDV fleet is reduced to 100%.

Figure 3 displays the results in graphical format, and Table 2 shows the results in tabular format. Results are shown for a 24-hour and a 12-hour night charging period to illustrate the impacts of a constrained charging period to 12 hours (6 pm to 6 am). Even when constraining the battery charging to the night period, a significant fraction of the regional vehicle fleet could still be supported with the existing grid infrastructure. Furthermore, additional vehicles could be supported if one makes the reasonable assumption that PHEVs will not be electrified clones of existing vehicles, but optimally

designed for fuel efficiency, regardless the “fuel” source. Finally, charging capability can be extended with the addition of generation from traditionally “intermittent” resources, such as wind turbines, because PHEVs provide a ready use for this power whenever it is available. The addition of new wind generation would significantly increase the fraction of PHEVs the WECC region could support.

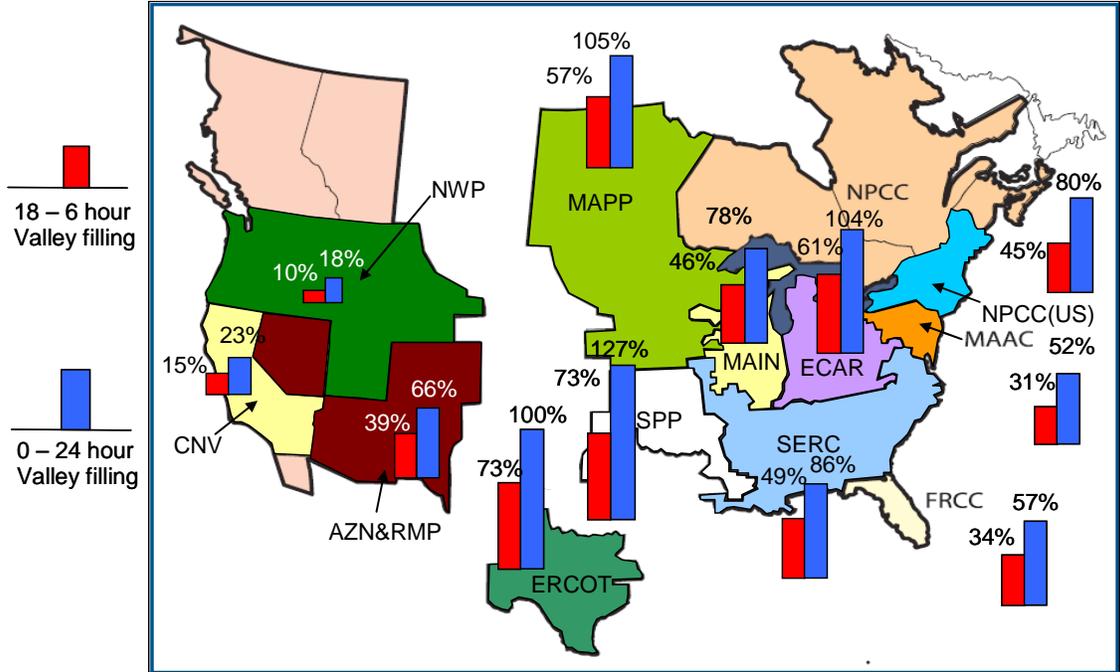


Figure 3: Technical Potential for Fueling the Regional Light Duty Vehicle Fleet with Available Electric Capacity

Table 2: Results of Technical Potential by Regions

Region	Total Number of Vehicles in Mill.	24-Hour Valley Filling	6 pm–6 am Valley Filling	24-Hour Valley Filling	6 pm–6 am Valley Filling
		Technical Potential in %		Technical Potential in Mill. Vehicles	
ECAR	27.7	104	61	28.6	16.8
ERCOT	15.5	100	73	15.5	11.3
MAAC	20.0	52	31	10.4	6.2
MAIN	16.7	78	46	13.1	7.7
MAPP	5.8	105	57	6.1	3.3
NPCC (U.S.)	19.6	80	45	15.6	8.9
FRCC	11.5	57	34	6.5	3.9
SERC	37.8	86	49	32.5	18.4
SPP	11.9	127	73	15.1	8.7
NWP	15.7	18	10	2.8	1.6
AZN&RMP	8.8	66	39	5.8	3.4
CNV	25.8	23	15	6.0	3.9
National Average*	216.9	73	43		

* Weighted average of all regions. Those regions with technical potential greater than 100% are assumed to export to regions with potential less than 100%. ERCOT’s technical potential is truncated from 136% to 100% because of negligible transfer capability out of ERCOT.

Results of Emissions Impacts

The conversion of LDVs to PHEVs has significant implications to overall emissions as electricity displaces gasoline. The net balance in the emissions of this fuel displacement process along the entire fuel cycle from the extraction of the primary energy to the final conversion in the vehicle into useful energy is discussed below.

For the nation as a whole, the total greenhouse gases are expected to be reduced by 27% from the projected penetration of PHEVs. The key driver for this result is the overall improvement in efficiency along the electricity generation path compared to the entire conversion chain from crude oil to gasoline to the combustion process in the vehicle. Fundamental to this result is the assumption that a PHEV by itself would be more efficient than a conventional gasoline car because of the regenerative braking capability that stores the kinetic energy in the battery during deceleration and because the engine operates at near optimal conditions more of the time than in conventional vehicles. On a regional basis, the greenhouse gas emission improvements could be as large as 40%, as in ERCOT, which has a large penetration of natural-gas plants. Conversely, the improvement in greenhouse gas emission could be zero or slightly negative for the MAPP region with essentially all coal generation (see Table 3).

Total volatile organic compounds (VOCs) and carbon monoxide (CO) emissions would improve radically by 93% and 98%, respectively, as a result of eliminating the use of the internal combustion engine. The VOC emissions reduction may be significantly over-estimated because PHEVs will still have gasoline in their tanks and vent to the atmosphere during refueling and to some extent while parked and during driving. The total nitrogen oxides (NO_x) emissions are significantly reduced (31%), primarily because of the avoidance of the internal combustion process in the vehicle as well as eliminating the refining process to produce gasoline.

The total particulate emissions (PM₁₀) are likely to increase nationally by 18%, caused primarily by increased dispatch of coal-fired plants. As can be seen in Table 3, however, in regions with a large contribution to the marginal generation from natural-gas fueled plants, the total particulate emission could improve. The total SO_x emissions are increased at the national level by about 125%, also caused by coal-fired power plants. However, while the particulate and SO_x emissions are expected to increase in total, they would be removed from the urban areas to the locations of the power plants, commonly at a considerable distance from the large urban population. All urban emissions are expected to significantly improve (see Table 3).

It should be noted that with the emergence of PHEV, the emission sources will shift from millions of individual vehicles to a few hundred central generation facilities. The economics for emission reduction and carbon sequestration technologies may look much more attractive when installed at central power plants rather than in motor vehicles, especially when the costs are spread over longer operating periods and billions of additional kilowatt hours.

Table 3: Emissions Results Using the GREET Model

	ECAR	ERCOT	MACC	MAIN	MAPP	NPCC	FRCC	SERC	SPP	NWP	AZN& RMP	CNV	U.S. total
Power Generation Composition													
Natural Gas	32%	94%	74%	42%	1%	91%	69%	57%	78%	43%	63%	93%	
Coal	68%	6%	26%	58%	99%	9%	31%	43%	22%	57%	37%	7%	
Emissions Ratio (Electric Vehicle/Gasoline Vehicle)													
GHGs	0.87	0.60	0.69	0.83	1.01	0.61	0.71	0.76	0.66	0.84	0.73	0.61	0.73
VOC: Total	0.11	0.04	0.06	0.10	0.14	0.04	0.07	0.08	0.06	0.10	0.07	0.04	0.07
CO: Total	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
NOx: Total	1.02	0.38	0.59	0.93	1.35	0.41	0.64	0.76	0.54	0.93	0.71	0.39	0.69
PM10: Total	1.55	0.81	1.06	1.45	1.94	0.86	1.13	1.26	0.99	1.46	1.19	0.84	1.18
SOx: Total	3.94	0.42	1.68	3.59	5.96	0.64	2.05	2.67	1.34	3.77	2.35	0.53	2.25
VOC: Urban	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CO: Urban	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx: Urban	0.10	0.11	0.11	0.10	0.09	0.11	0.11	0.10	0.11	0.10	0.10	0.11	0.10
PM10:Urban	0.60	0.62	0.62	0.60	0.58	0.62	0.61	0.61	0.62	0.61	0.61	0.62	0.61
SOx: Urban	0.35	0.04	0.14	0.30	0.51	0.05	0.17	0.22	0.12	0.31	0.20	0.04	0.19

Potential to Reduce Dependency on Foreign Crude Oil Imports

One of the key premises of the PHEV technology, from a policy perspective, is the potential to reduce the U.S. dependency on imports of foreign crude oil. To illustrate the potential benefits of a conversion from a gasoline-driven LDV fleet to PHEVs, we estimated a displacement potential on the total national consumption of gasoline. This figure is an upper-bound estimate on the gasoline displacement potential. The realizable potential will most likely be smaller to account for the long-distance driving above 33 miles per day and the few days during the year when PHEVs may not be fully charged because of maximum peak conditions on the grid. Figure 4 shows that in 2005, the United States consumed gasoline at a rate that required 9.1 million barrels of crude oil per day [EIA, 2005]. Considering that the LDV fleet consumes 97% of the entire gasoline supply, the conversion of 73% of the LDV fleet to PHEVs could reduce gasoline consumption by a crude oil equivalence of 6.5 million barrels per day (MMBpd). This reduction in the U.S. gasoline consumption is the equivalent of 52% of foreign petroleum imports.

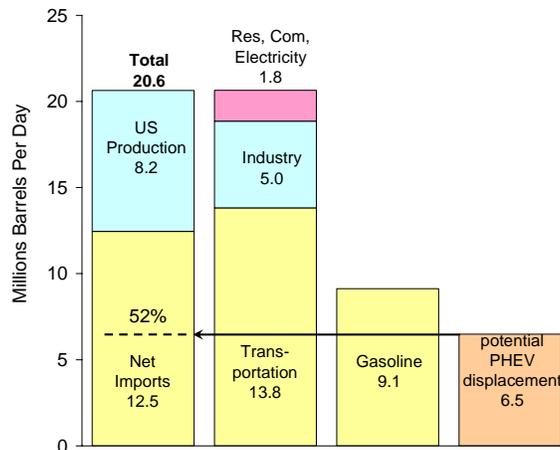


Figure 4: Petroleum Supply, Consumptions and PHEV Displacement Potential [EIA, 2005]

Other Electric System Impacts

Providing 73% of the daily energy requirements of the U.S. LDV fleet with electricity would add approximately 910 billion kWh, an increase of about 24% of the total U.S. annual generation in 2002 [EIA, 2006b]. Without further infrastructure investments, the current electric power system would be heavily loaded for most hours of all days. Planned outages for plant maintenance would likely need to occur more frequently, making it more difficult to schedule maintenance. Furthermore, the overall system reliability could be reduced in this high utilization scenario as less reserve capacity is available to the system operators for managing system emergencies. “Smart” PHEV charging systems that recognize grid emergencies could mitigate the extent and severity of these grid emergencies. Vehicle-to-grid (V2G) concepts (not examined in this study) could potentially provide additional reliability enhancements using the storage capacity of the PHEV by reversing the power flow from the battery to the grid [Kempton, 2005a and 2005b]. Particularly with high system utilization, smart loads become an attractive reliability resource that could become more prevalent with current communications and automation investments.

The valley-filling methodology is predicated on the notion that the entire PHEV load is managed to fit perfectly into the valley without setting new peaks. One approach to approximate a load management is via electricity pricing that discourages customers from charging the PHEVs during peak periods and encourages them to charge during off-peak periods. The PHEV charger would need to be a smart device equipped with communications or—in the most simple way—a timer to prevent charging during peak periods.

While we rationalized that PHEV charging could be done without setting new system peaks and causing new transmission congestions, it represents a significant shift from a power system with peaks and valleys to one that is constantly loaded. While the bulk power system is designed to operate reliability at these levels during peak periods, sustained operation at these levels may reveal new constraints. For example, there may be intra-regional transmission constraints that come into place when transmission lines are heavily loaded for extended periods. Specific and detailed regional studies would reveal these delivery constraints. Similarly, the distribution system may impose some additional constraints on the delivery limits to off-peak PHEV charging. System components such as transformers may impose additional constraints on the delivery limit because they may not be designed to sustain a constant high loading without a period of lower load conditions during which the equipment can cool down. Preliminary analyses of residential distribution feeders load data suggest that the characteristics of the residential load shapes are similar in proportion to the peak and valley as observed at the regional system level.⁵ This provides some evidence that the additional load could potentially be accommodated in the off-peak valley without setting a new peak during the former off-peak period. However, additional analyses of impacts on the distribution system with a different composition of industrial, commercial, and residential customers are warranted to investigate the assumptions made in this study.

The expected anti-cyclical load shape of the emerging new PHEV load will flatten the overall load duration characteristics, and as a result, it is likely to change the mix of future power plant types and technologies with important implications to base-load coal and nuclear technologies. This is potentially beneficial for these power generation technologies, as they typically have the lowest power production

⁵ Based on substation and feeder data from predominantly residential feeders in Southern California Edison’s and Allegheny Power’s service territory.

costs. Similarly, PHEVs provide a ready source of demand for power from intermittent renewable resources that may allow greater utilization of power from the wind and sun than otherwise.

In the short run, the expected increased utilization scenario will affect wholesale electricity markets as supplies of generation resources remain tight over longer periods. One result could be an upward pressure on wholesale electricity prices, although the persistence of higher prices will induce investments in new generation and transmission capacity. In the long-term, the supply will follow the load to meet the growing demand. The development of a new transportation load may facilitate financing of low cost base load generation and renewables that is currently lacking in the marketplace. The potential for short-term price increases and longer-term price and rate decreases needs to be analyzed further and considered as part of the public policy debate. A fuller discussion of the economic assessment of PHEVs is in the companion paper (Part II: Economic Assessment), which examines impacts to the revenue requirements and the electric rates in a fully regulated utility environment.

SUMMARY

The results of the analysis are listed below:

- The existing electricity infrastructure as a national resource has sufficient available capacity to fuel 84% of the nation's cars, pickup trucks, and SUVs (198 million) or 73% of the light duty fleet (about 217 million vehicles) for a daily drive of 33 miles on average.
- There are significant emissions impacts resulting if the gasoline-based LDV fleet were to transition to a PHEV technology. Greenhouse gases and some criteria emissions would be reduced based on total emission figures. Particulates and SO_x emissions would increase as a result of increased dispatch of coal-fired power plants. There are regional differences that depend upon the mix of coal and natural-gas-fired power plants. All emissions in urban areas are expected to improve because of the shifting of the emission source from millions of individual vehicles in population centers to central generation plants that are traditionally located away from population centers.
- A shift from gasoline to PHEVs could reduce the gasoline consumption by 6.5 MMBpd, which is equivalent to 52% of the U.S. petroleum imports.
- Several other grid-related impacts are likely to emerge when adding significant new load for charging PHEVs. Higher system loading could impact the overall system reliability as the entire infrastructure is utilized near its maximum capability for long periods. "Smart" PHEV charging systems that recognize grid emergencies could mitigate the extent and severity of grid emergencies. Near maximum utilization of the nation's power plants is likely to impact wholesale electricity markets. The mix of future power plant types and technologies may change as a result of the flatter load-duration curve favoring more base-load power plants and intermittent renewable energy resources.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Office of Electricity Delivery and Energy Reliability of the U.S. Department of Energy (DOE) for support of the analysis. Particular thanks are extended to the DOE program manager, Eric Lightner, who provided helpful directions for writing this paper.

CONTACT

Michael Kintner-Meyer, Ph.D., Pacific Northwest National Laboratory. Phone: 509.375.4306. Email: Michael.Kintner-Meyer@pnl.gov.

Robert Pratt, Pacific Northwest National Laboratory. Phone: 509.375.3648. Email: Robert.Pratt@pnl.gov.

REFERENCES

BPA. 2003. Federal Columbia River Power System (Bonneville Power Administration) Brochure: available online: <http://www.bpa.gov/corporate/BPANews/Library/images/Dams/>.

Davis, S; Diegel, S. 2006. Transportation Energy Data Book . 25th Edition. p. 8-15. ORNL-6974. Center for Transportation Analysis, Oak Ridge National Laboratory, Oak Ridge, TN.

DOT. 2002. Highway Statistics 2001. Table 5-1: Motor-Vehicle Registrations: 2001. U.S. Department of Transportation, Federal Highway Administration, Washington, DC.

DOE. 2003. Technology Options For the Near and Long Term. A Compendium of Technology Profiles and Ongoing Research and Development at Participating Federal Agencies. Section 1.3.2. DOE/PI-0002. Department of Energy, Washington, DC.

DOT. 2003. Highlights of the 2001 National Household Travel Survey. BTS03-05. Table A-8. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington DC.

Duvall, M. 2002. Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles. Final Report 1006892. Electric Power Research Institute. Palo Alto, CA.

Duvall, M. 2003. Electricity as an Alternative Fuel: Rethinking Off-Peak Charging. Plug-in HEV workshop. Electric Power Research Institute. Palo Alto, CA.

Duvall, M. 2004. Advanced Batteries for Electric Drive Vehicles. A Technology and Cost-Effectiveness Assessment for Battery Electric Vehicles, Power Assist Hybrid Electric Vehicles, and Plug-in Hybrid Electric Vehicles. Final Report. 1009299. Electric Power Research Institute, Palo Alto, CA.

EIA. 2005. Annual Energy Review, 2005. Based on Energy Flow Diagram p. 3. DOE/EIA-0384(2005), July 2006, Energy Information Administration, Washington, DC.

EIA. 2005b. Electric Power Annual 2005. Energy Information Administration. DOE/EIA-0348(2005). Energy Information Administration, Washington, DC.

- EIA. 2006a. The Electricity Market Module of the National Energy Modeling System. Model Documentation Report. DOE/EIA M068(2006). Energy Information Administration, Washington, DC.
- EIA. 2006b. Annual Energy Outlook 2006. Supplemental Tables. DOE/EIA-0383(2006). Energy Information Administration, Washington, DC.
- EIA. 2006c. The Electricity Market Module of the National Energy Modeling System. Model Documentation Report. DOE/EIA-M068(2006).
- Graham, B. 2005. EPRI and Its Plug-In Hybrid Vehicle Initiative. Presentation. Electric Power Research Institute, Palo Alto, CA.
- GREET. 2001. Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies. Argonne National Laboratory, ANL/ESD/TM-163.
- Hu, P. and Young, J. 1994. 1990 Nationwide Personal Transportation Survey Databook. Vol. 1 and 2. Oak Ridge National Laboratory, Oak Ridge, TN.
- Kempton, W.; Tomić, J. 2005a. Vehicle-to-Grid Power Implementation: From Stabilizing the Grid to Supporting Large-Scale Renewable Energy. Journal of Power Sources. Vol. 144, Issue 1, pages 280-294. Elsevier, Atlanta, GA.
- Kempton, W.; Tomić, J. 2005b. Vehicle-to-Grid Power Fundamentals: Calculating Capacity and Net Revenue. Journal of Power Sources. Vol. 144, Issue 1, pages 268-279. Elsevier, Atlanta, GA.
- Potomac. 2006. 2005 State of the Market Report for the ERCOT Wholesale Electricity Markets. Potomac Economics, Ltd. Advisor to the Wholesale Market Oversight Public Utility Commission of Texas.
- Taylor, D. 2003. Plug-in HEVs. Presentation. Southern California Edison.

APPENDIX A

The figures below show for selected regions a daily load profile for the summer and winter seasons. Each figure shows: a) average seasonal load profile, b) generation dispatch to meet average seasonal load profile, c) valley-filling generation potential shown as hatched bars and denoted in the legend as “additional” plant type, and d) seasonal peak load day.

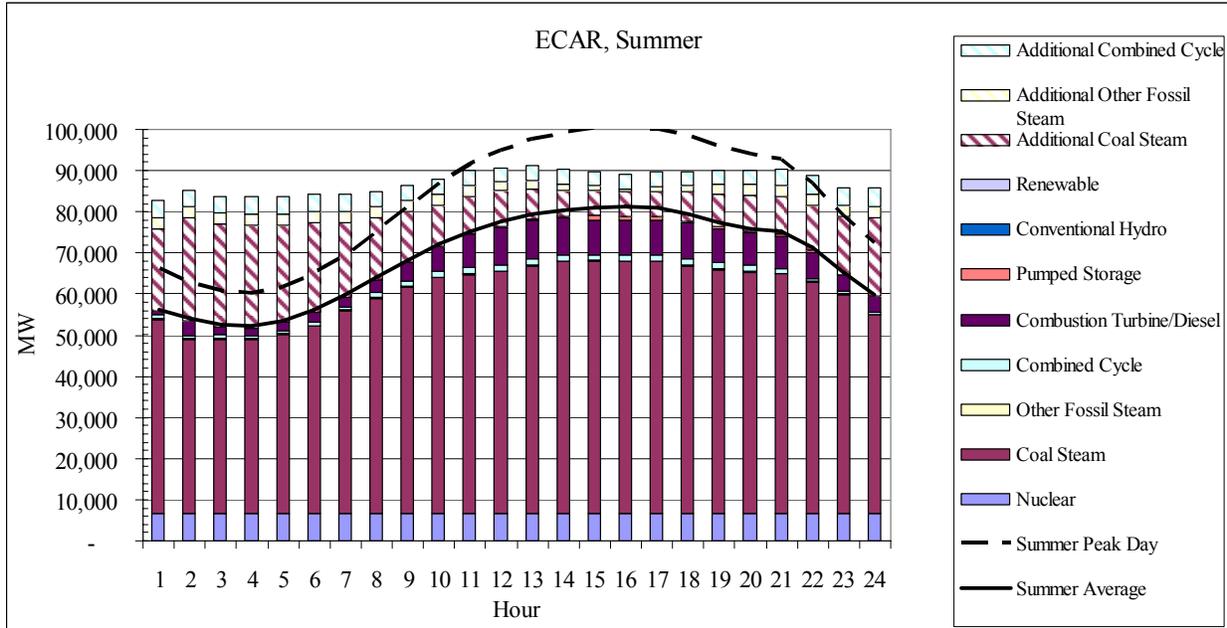


Figure A.1: ECAR Dispatch for Summer Average Load Profile, Valley-Filling Potential, and Peak Day

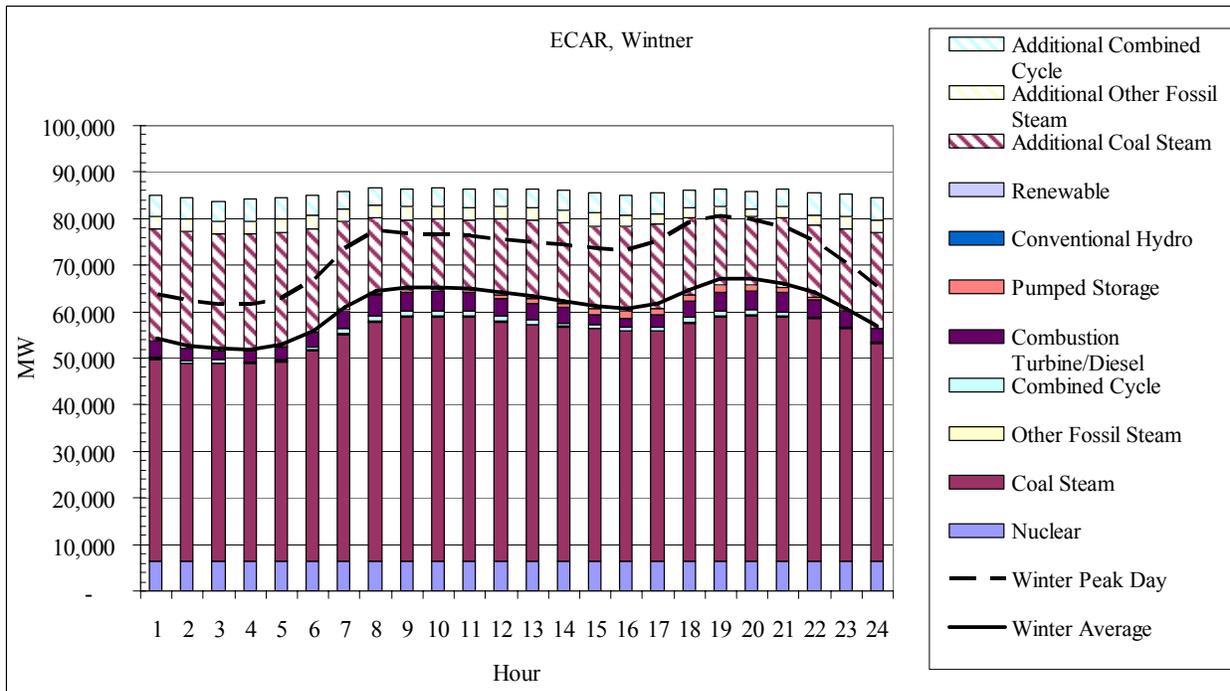


Figure A.2: ECAR Dispatch for Winter Average Load Profile, Valley-Filling Potential, and Peak Day

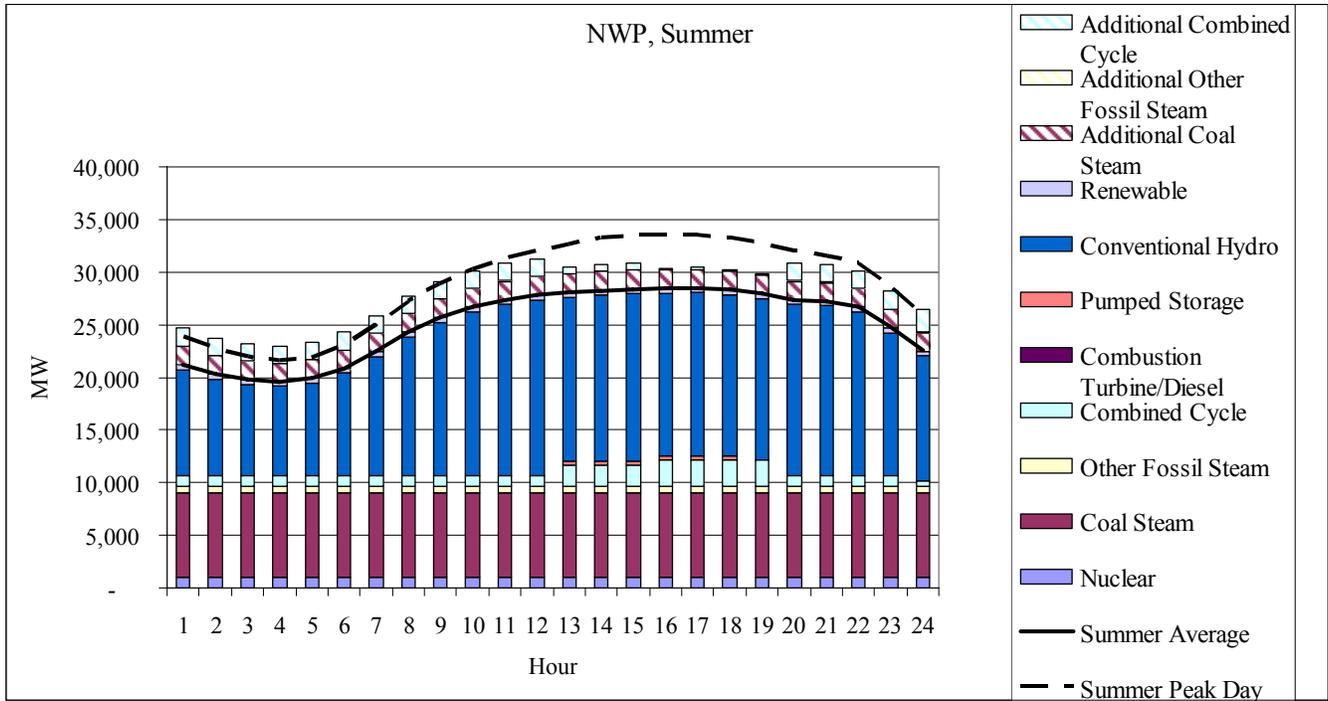


Figure A.3: NWP Dispatch for Summer Average Load Profile, Valley-Filling Potential, and Peak Day

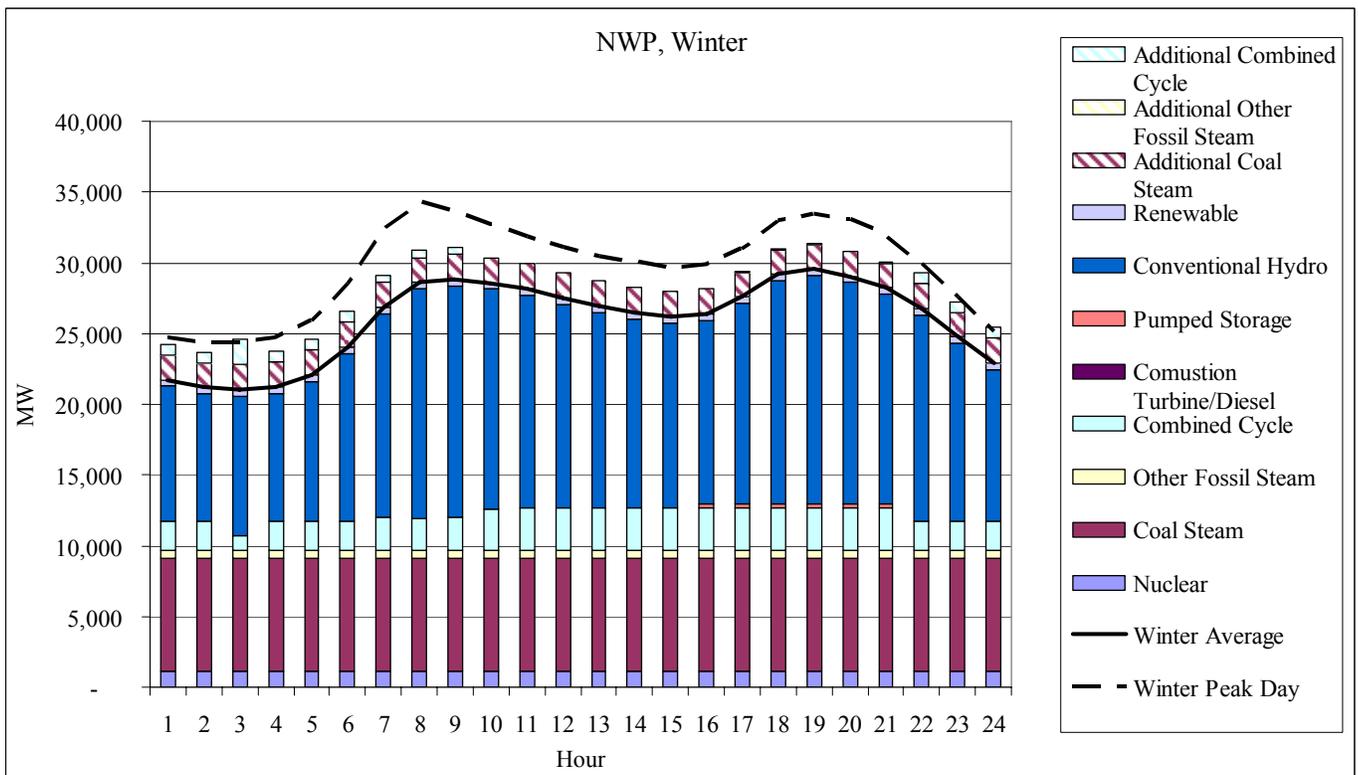


Figure A.4: NWP Dispatch for Winter Average Load Profile, Valley-Filling Potential, and Peak Day

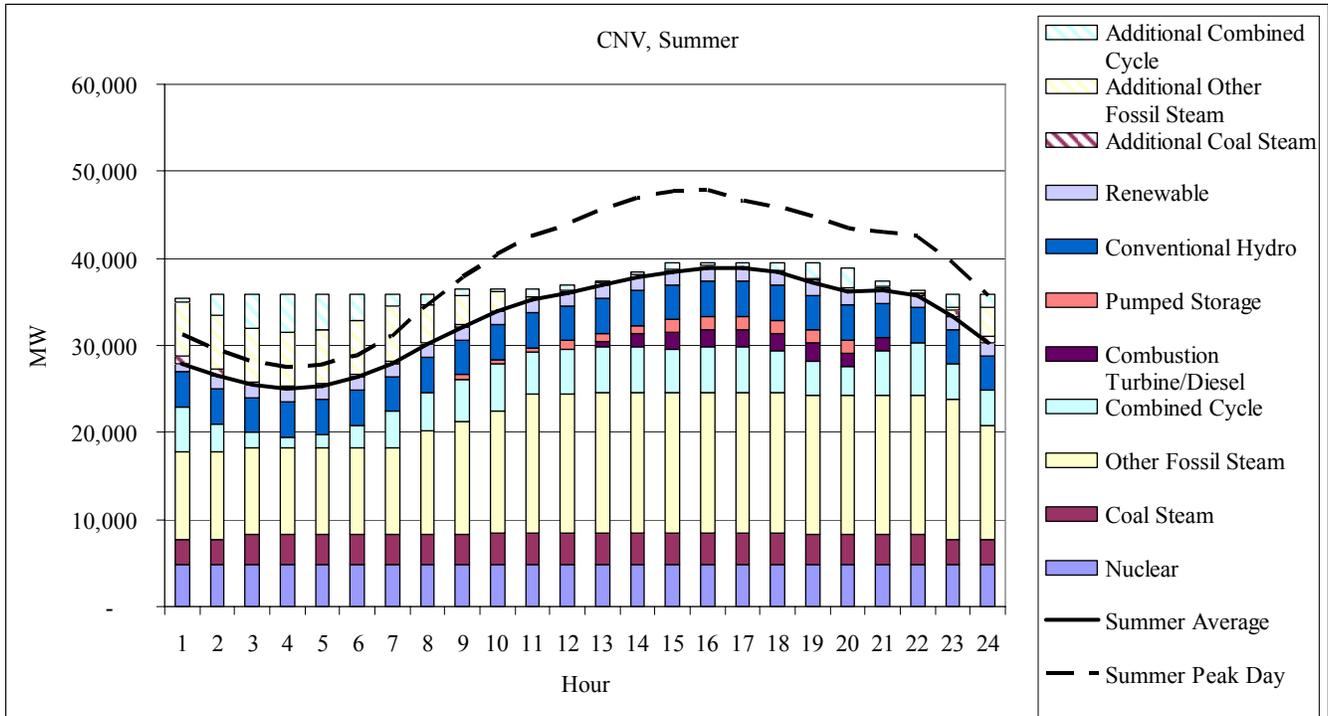


Figure A.5: CNV Dispatch for Summer Average Load Profile, Valley-Filling Potential, and Peak Day

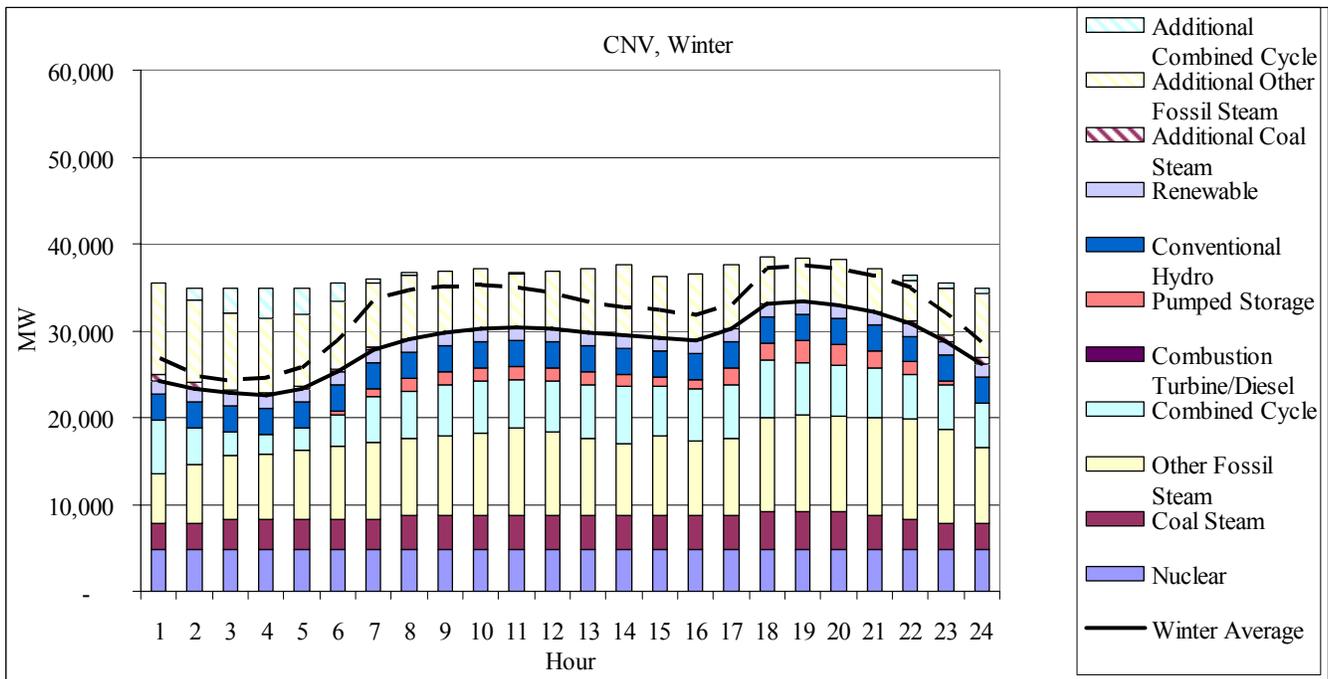


Figure A.6: CNV Dispatch for Winter Average Load Profile, Valley-Filling Potential, and Peak Day